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Breymesser et al.

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(54) **IMPLANTATION APPARATUS WITH ION BEAM DIRECTING UNIT, SEMICONDUCTOR DEVICE AND METHOD OF MANUFACTURING**

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H01J 37/317	(2006.01)
H01L 29/06	(2006.01)
H01L 29/744	(2006.01)
H01L 29/45	(2006.01)

(52) **U.S. Cl.**

CPC ***H01J 37/1477*** (2013.01); ***H01J 37/20*** (2013.01); ***H01J 37/3171*** (2013.01); ***H01L 29/0615*** (2013.01); ***H01L 29/0657*** (2013.01); ***H01L 29/744*** (2013.01); *H01J 2237/20214* (2013.01); *H01L 29/45* (2013.01)

(58) **Field of Classification Search**

USPC 438/499, 514, 527; 257/E21.334, 257/E21.337, E29.109

See application file for complete search history.

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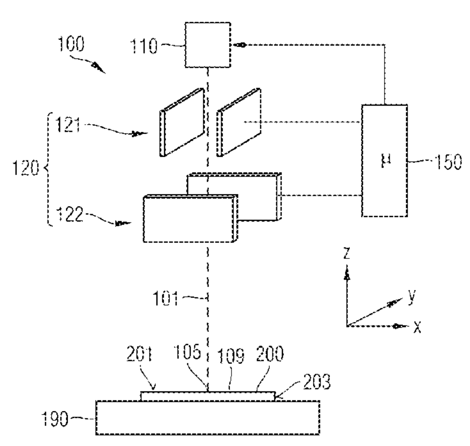
(57) **ABSTRACT**

An ion implantation apparatus includes an ion beam directing unit, a substrate support, and a controller. The controller is configured to effect a relative movement between an ion beam passing the ion beam directing unit and the substrate support. A beam track of the ion beam on a substrate mounted on the substrate support includes circles or a spiral.

7 Claims, 8 Drawing Sheets



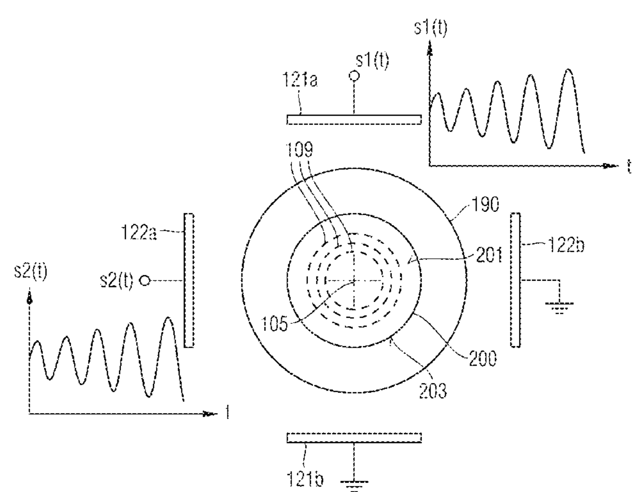


FIG 1A

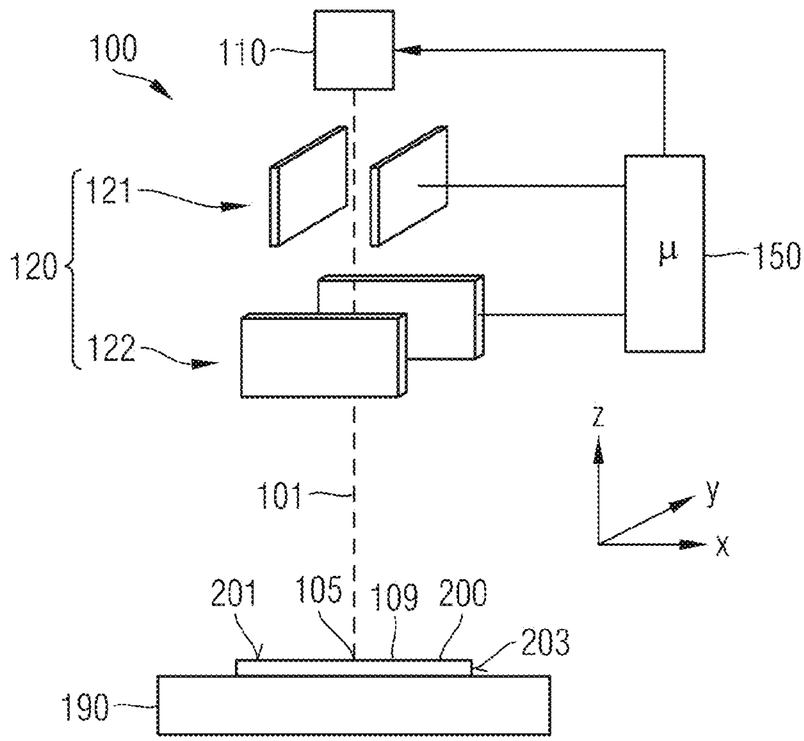

100
110
121
120
122
150
μ
z
y
x
101
201
105
109
200
203
190

FIG 1B

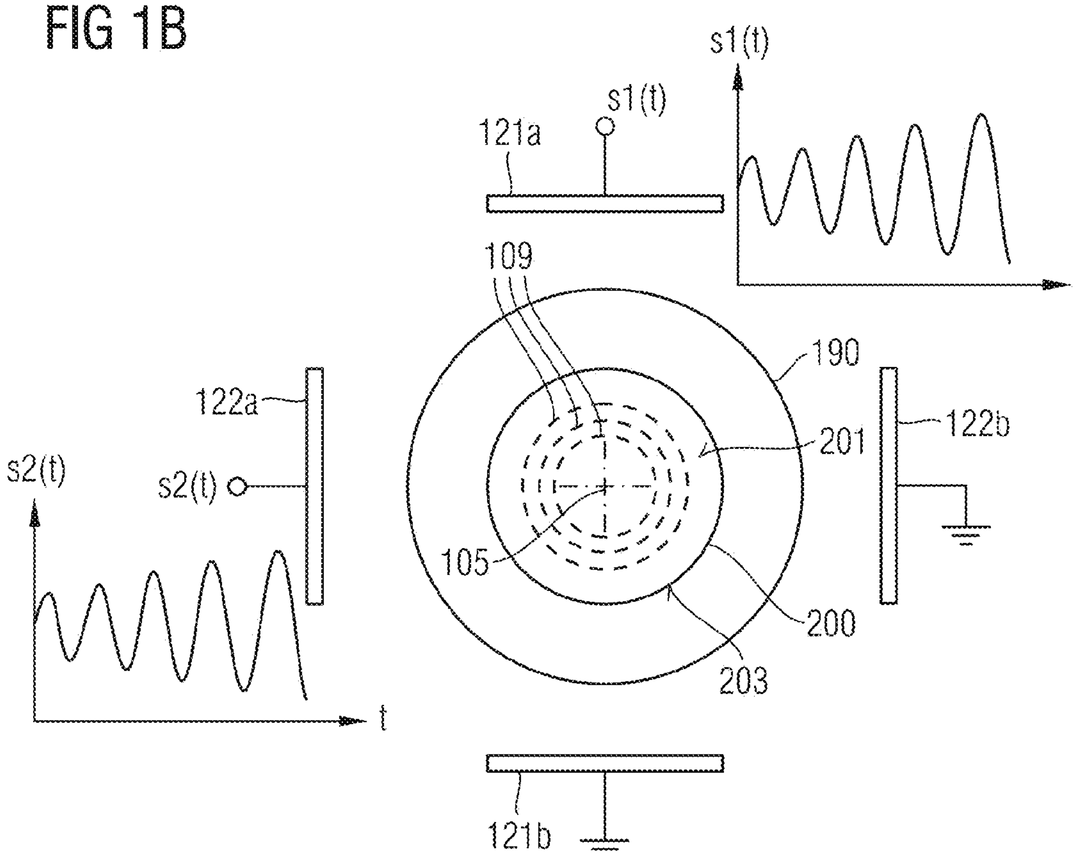

s1(t)
121a
s1(t)
t
109
190
122a
122b
s2(t)
s2(t)
201
105
200
203
t
121b

FIG 1C

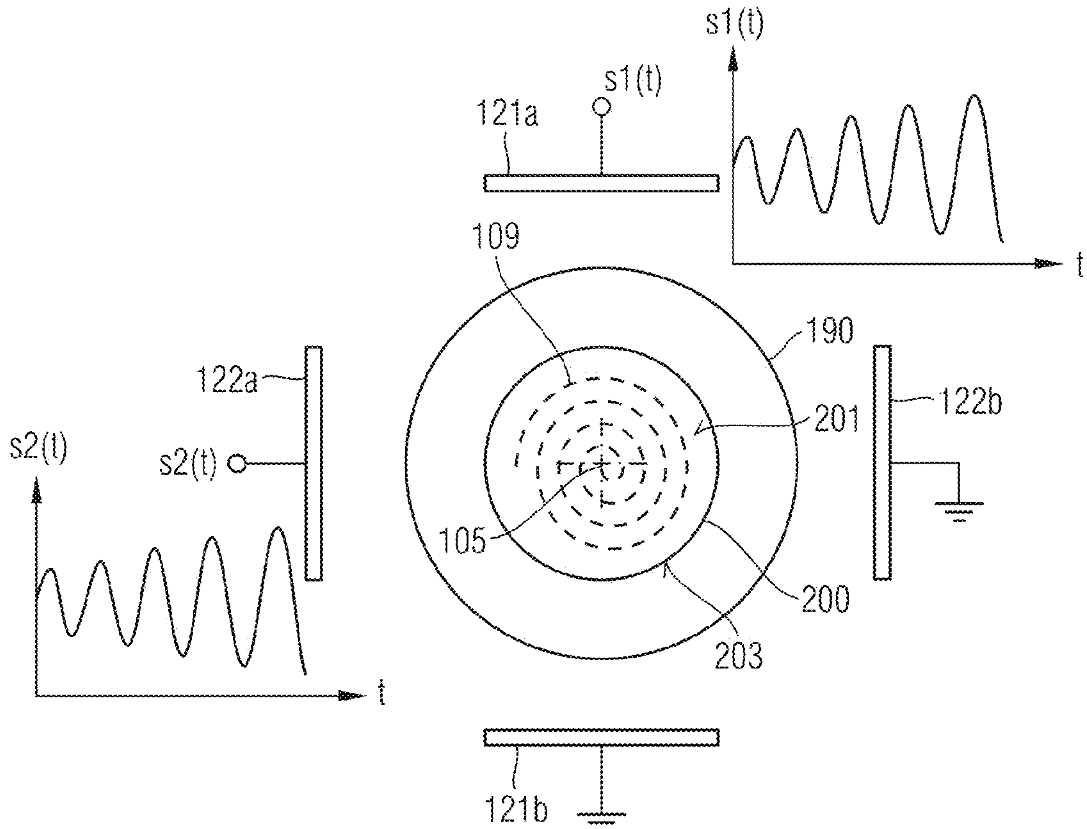

s1(t)
s1(t)
121a
t
109
190
122a
201
122b
s2(t)
s2(t)
105
200
203
t
121b

FIG 1D

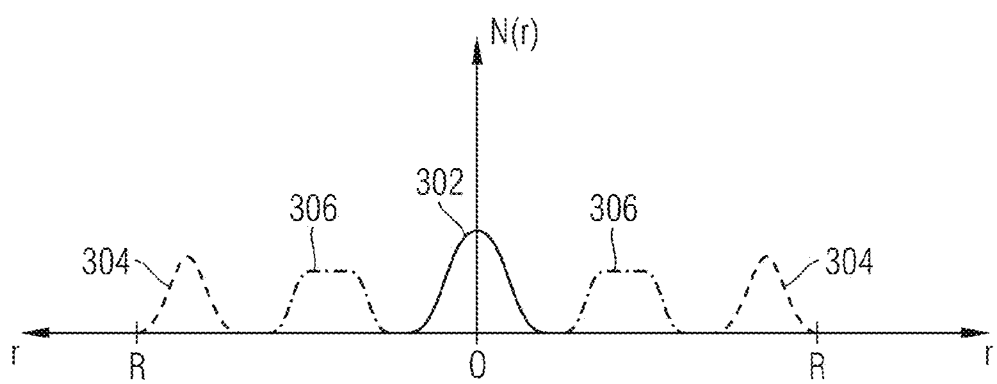

N(r)
302
306
306
304
304
r
R
0
R
r

FIG 2A

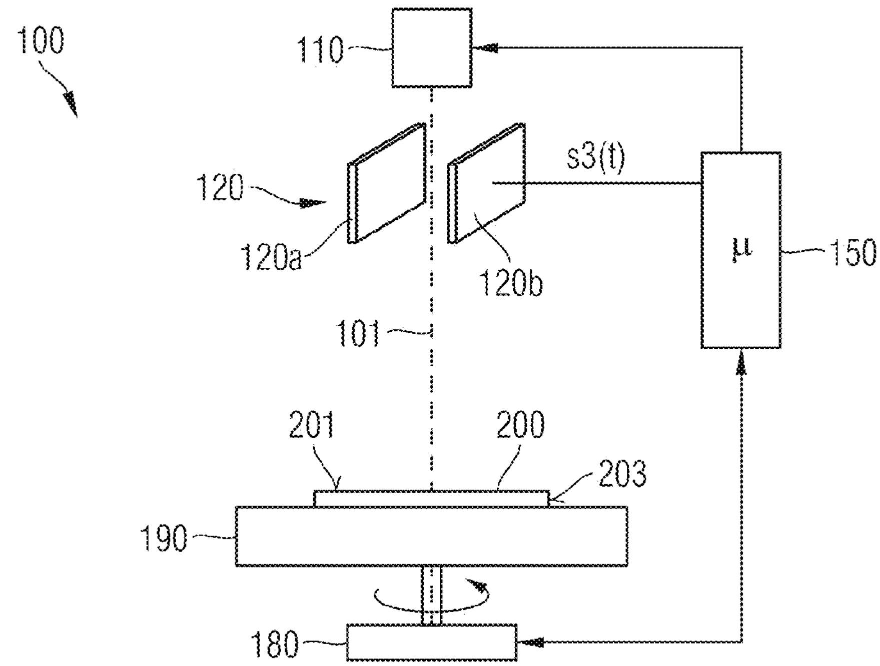

100
110
120
120a
120b
s3(t)
μ
150
101
201
200
203
190
180

FIG 2B

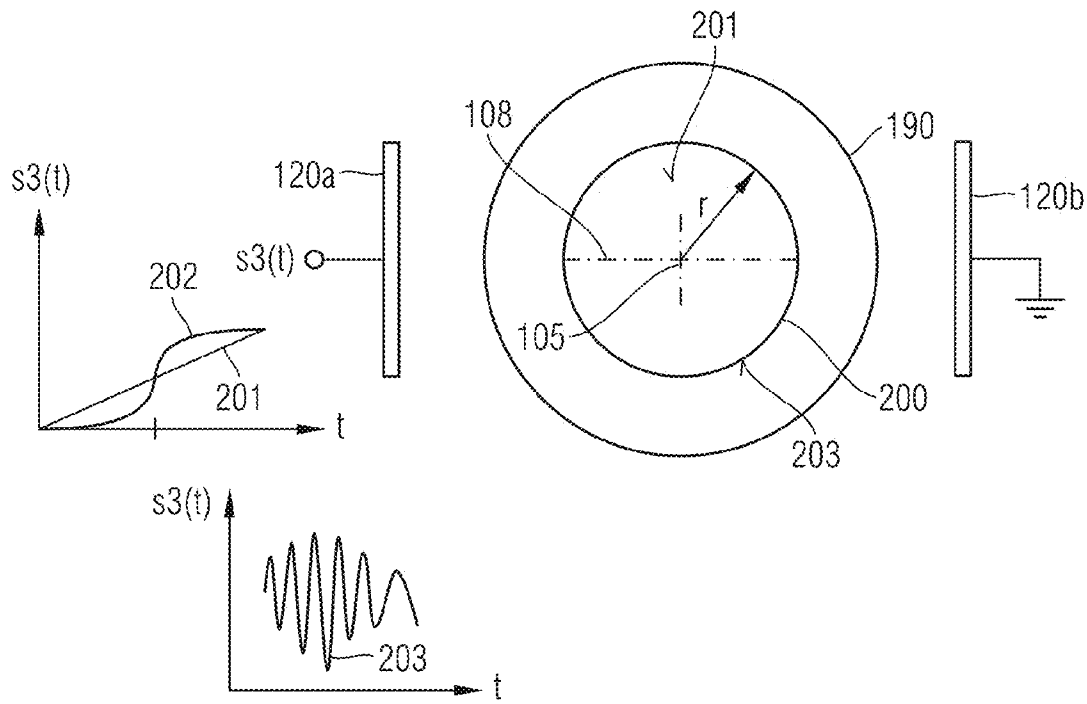

s3(t)
202
201
t
120a
s3(t)
108
201
r
190
120b
105
200
203
s3(t)
203
t

FIG 3A

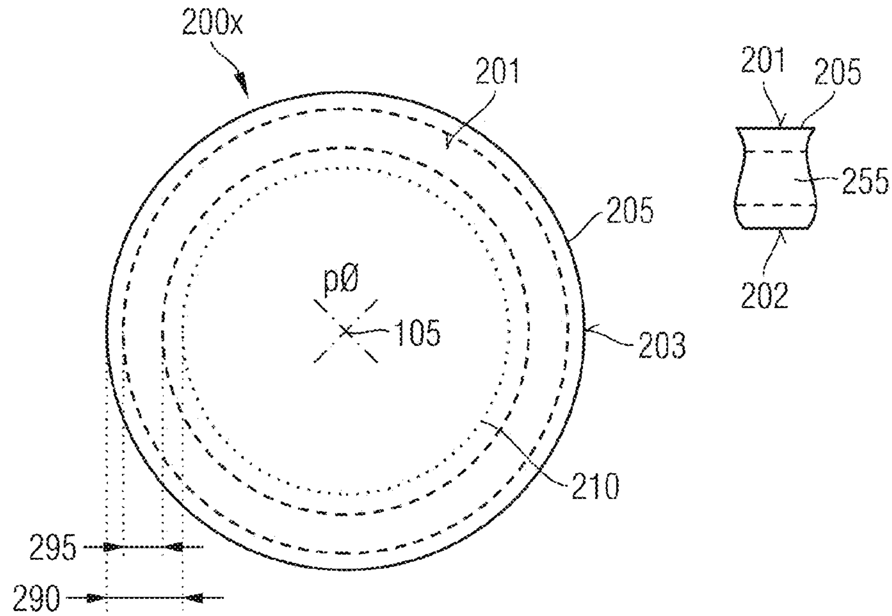

200x
201
205
203
pØ
105
210
295
290
201
205
255
202

FIG 3B

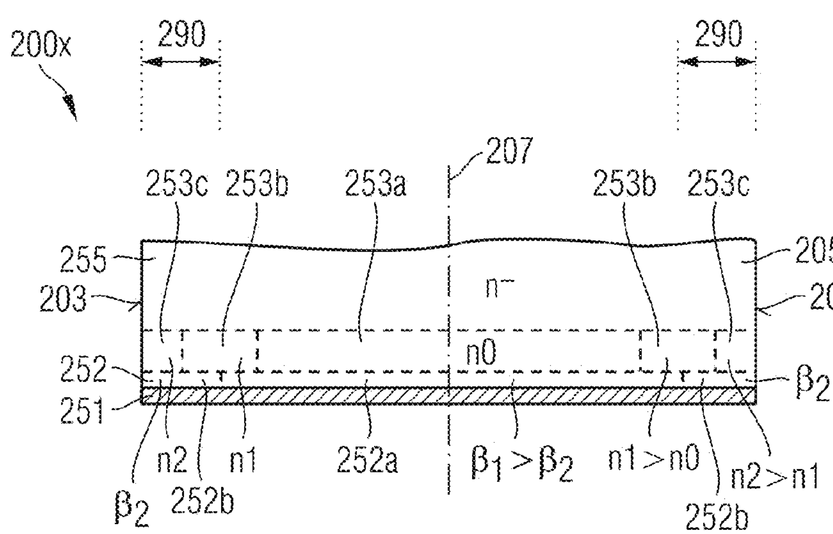

200x
290
290
207
253c
253b
253a
253b
253c
255
205
203
203
n−
n0
252
251
β2
β2
n2
252b
n1
252a
β1 > β2
n1 > n0
n2 > n1
252b

FIG 3C

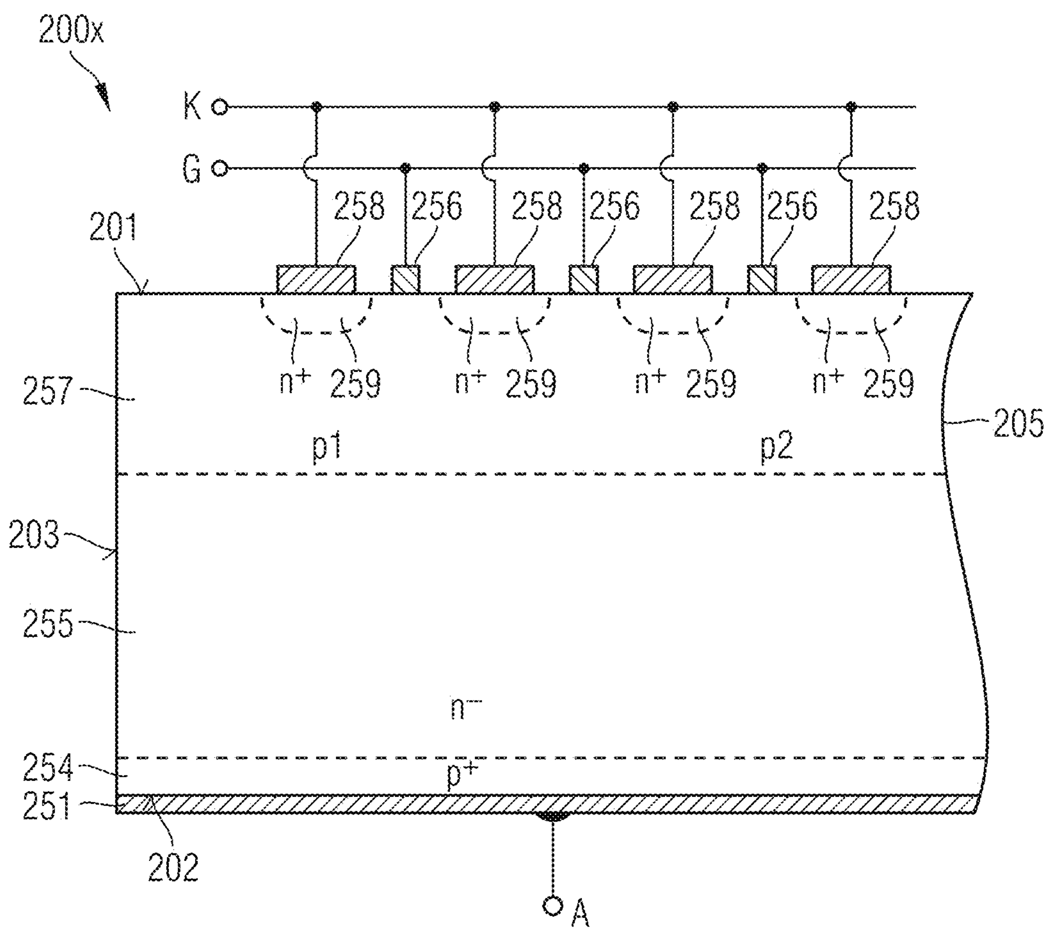

200x
K
G
258
256
258
256
258
256
258
201
n+
259
n+
259
n+
259
n+
259
257
205
p1
p2
203
255
n−
254
p+
251
202
A

FIG 4A

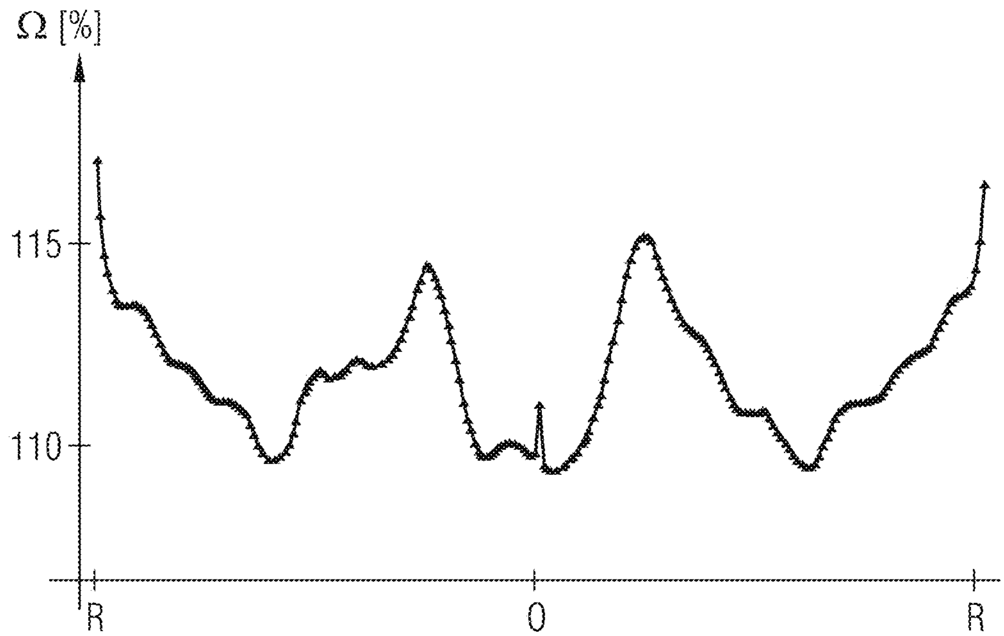


FIG 4B

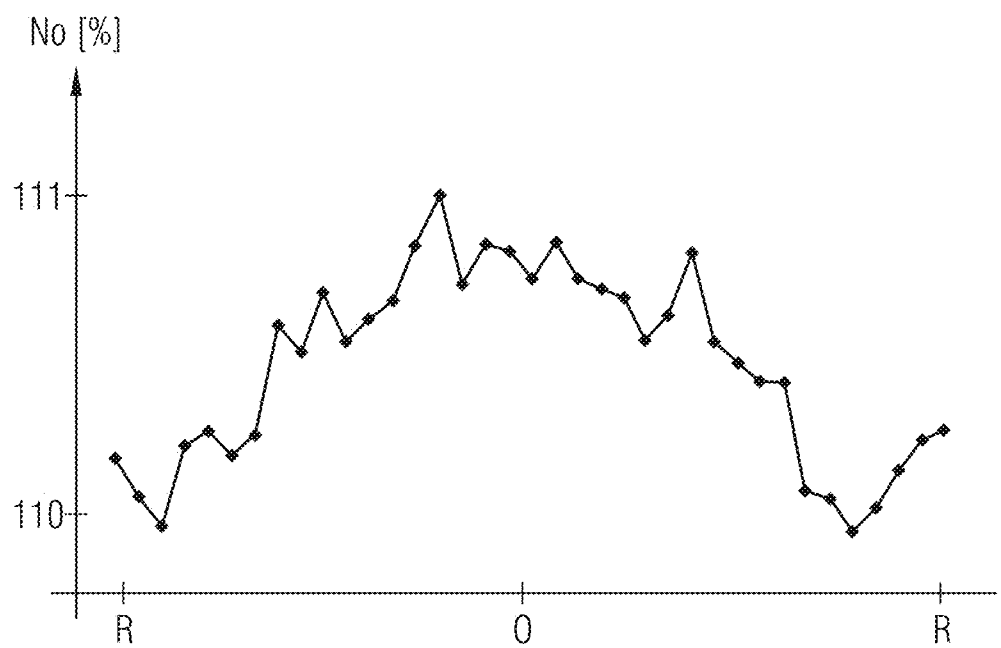


FIG 4C

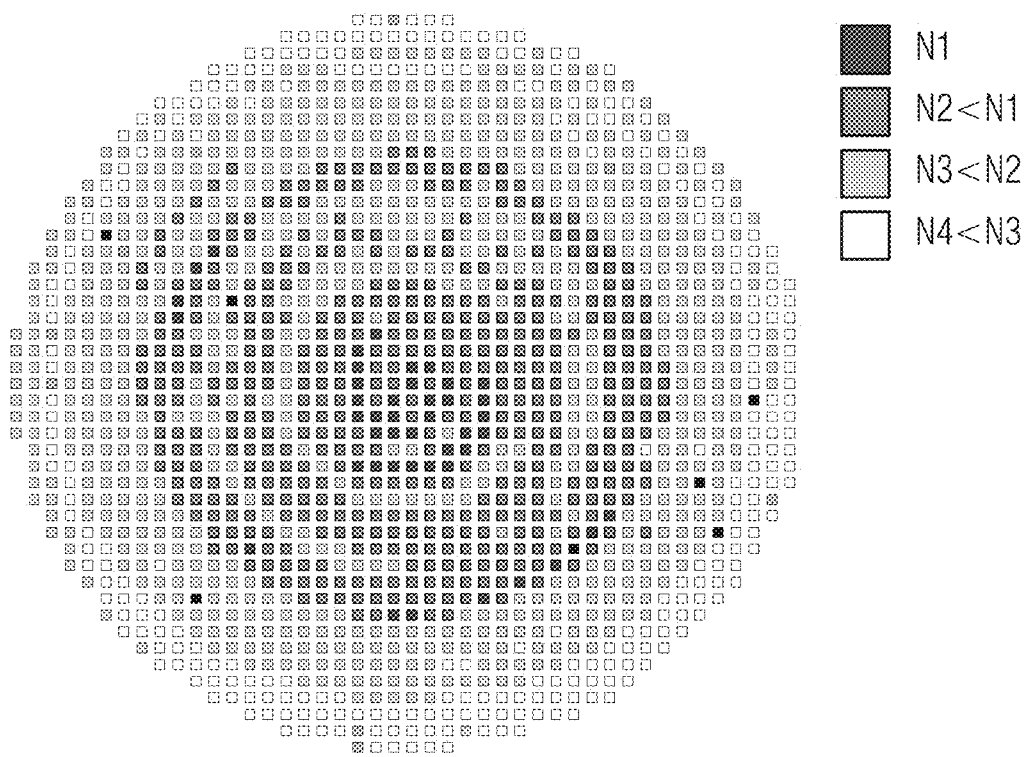


FIG 4D

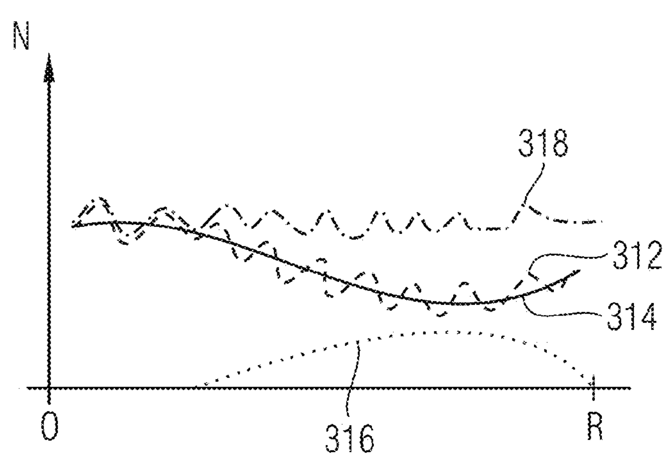
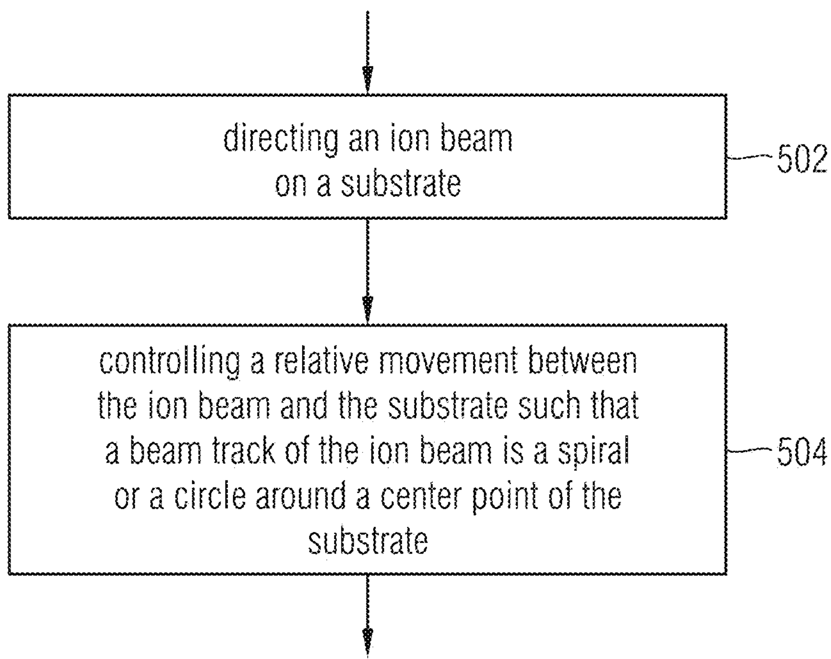


FIG 5


directing an ion beam on a substrate
502
controlling a relative movement between the ion beam and the substrate such that a beam track of the ion beam is a spiral or a circle around a center point of the substrate
504

IMPLANTATION APPARATUS WITH ION BEAM DIRECTING UNIT, SEMICONDUCTOR DEVICE AND METHOD OF MANUFACTURING

BACKGROUND

Ion implanters with high current accelerator systems and ion beam currents of more than 2 mA emit ion beams with a diameter of several centimeters. Several semiconductor substrates may be mounted on a substrate carrier that rotates during the ion implant. Ion implanters with medium current accelerator systems and ion beam currents of about 1 mA emit ion beams with a diameter of about 1 cm. An electrostatic deflection system deflects the ion beam along two orthogonal scan directions. For implanting impurities in a semiconductor substrate the ion beam linearly scans the semiconductor substrate along parallel lines or zig-zag paths. The implant dose may be locally modified by omitting lines or the line feed for one or more linear scans or by varying the scan speed.

There is a need for improving ion implanters and the methods of ion implanting.

SUMMARY

According to an embodiment an ion implantation apparatus includes an ion beam directing unit, a substrate support, and a controller. The controller is configured to effect a relative movement between an ion beam passing the ion beam directing unit and the substrate support wherein a beam track of the ion beam on a substrate mounted on the substrate support includes circles or a spiral.

According to another embodiment an ion implantation method includes directing an ion beam onto a substrate and controlling a relative movement between the ion beam and the substrate such that a beam track of the ion beam is a spiral or a circle around a center point of the substrate.

According to a further embodiment a semiconductor substrate includes a circular wafer-scale semiconductor body and in the semiconductor body a circular implant zone with a radial variation of doping around a center point of the semiconductor body.

Those skilled in the art will recognize additional features and advantages upon reading the following detailed description and on viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification. The drawings illustrate the embodiments of the present invention and together with the description serve to explain principles of the invention. Other embodiments of the invention and intended advantages will be readily appreciated as they become better understood by reference to the following detailed description.

FIG. **1**A is a schematic diagram illustrating an ion implantation apparatus according to an embodiment providing electrostatic deflection units for two lateral directions.

FIG. **1**B is a schematic plan view of a substrate according to an embodiment with an ion beam track on the substrate including concentric circles.

FIG. **1**C is a schematic plan view on a substrate according to an embodiment with an ion beam track on the substrate including a spiral.

FIG. **1**D is a schematic diagram illustrating circular impurity profiles according to embodiments.

FIG. **2**A is a schematic block diagram of an ion implantation apparatus according to an embodiment including a rotating substrate support.

FIG. **2**B is a schematic plan view of a substrate for illustrating a cross-sectional line between an ion beam plane and the substrate according to another embodiment.

FIG. **3**A is a schematic lateral cross-sectional view of a semiconductor device including circular impurity regions according to an embodiment related to charge carrier lifetime adjustment.

FIG. **3**B is a schematic cross-sectional view of a semiconductor device according to an embodiment related to a field stop layer with a circular variation of doping.

FIG. **3**C is a schematic cross-sectional view of a thyristor according to an embodiment related to a compensation of a variation of effective gate resistance.

FIG. **4**A is a diagram schematically illustrating a lateral profile of the specific resistance of a semiconductor wafer obtained from a Czochralski process for discussing effects of the embodiments.

FIG. **4**B is a diagram schematically illustrating an intrinsic oxygen distribution across a semiconductor wafer obtained from a Czochralski process for discussing effects of the embodiments.

FIG. **4**C is a diagram schematically illustrating a charge carrier density in chip areas of a semiconductor wafer obtained from a Czochralski process for discussing effects of the embodiments.

FIG. **4**D is a schematic diagram illustrating impurity distributions for illustrating a method of manufacturing semiconductor devices according to a further embodiment.

FIG. **5** is a schematic flow chart of an ion implantation method as well as a method of manufacturing semiconductor devices according to other embodiments.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof and in which are shown by way of illustrations specific embodiments in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural or logical changes may be made without departing from the scope of the present invention. For example, features illustrated or described for one embodiment can be used on or in conjunction with other embodiments to yield yet a further embodiment. It is intended that the present invention includes such modifications and variations. The examples are described using specific language, which should not be construed as limiting the scope of the appending claims. The drawings are not scaled and are for illustrative purposes only. For clarity, the same elements have been designated by corresponding references in the different drawings if not stated otherwise.

The terms “having”, “containing”, “including”, “comprising” and the like are open, and the terms indicate the presence of stated structures, elements or features but do not preclude additional elements or features. The articles “a”, “an” and “the” are intended to include the plural as well as the singular, unless the context clearly indicates otherwise.

The term “electrically connected” describes a permanent low-ohmic connection between electrically connected elements, for example a direct contact between the concerned elements or a low-ohmic connection via a metal and/or highly doped semiconductor. The term “electrically coupled” includes that one or more intervening element(s) adapted for signal transmission may be provided between the electrically coupled elements, for example elements that are controllable to temporarily provide a low-ohmic connection in a first state and a high-ohmic electric decoupling in a second state.

The Figures illustrate relative doping concentrations by indicating "−" or "+" next to the doping type "n" or "p". For example, "n^-" means a doping concentration which is lower than the doping concentration of an "n"-doping region while an "n^+"-doping region has a higher doping concentration than an "n"-doping region. Doping regions of the same relative doping concentration do not necessarily have the same absolute doping concentration. For example, two different "n"-doping regions may have the same or different absolute doping concentrations.

The ion implantation apparatus **100** in FIG. **1**A includes an ion beam source **110** emitting an ion beam **101**. The ion beam source **110** may include an ion source emitting the desired ions, for example protons, helium, donator or acceptor ions such as boron ions, phosphorus ions or arsenic ions, by way of example. The ion beam source **110** may further include an accelerator electrostatically accelerating the ions emitted by the ion source, a separation magnet for removing undesired impurity ions and a lens unit for focusing the ion beam **101**. According to an embodiment a diameter of the ion beam **101** is between 0.5 and 2.5 cm.

The ion implantation apparatus **100** further includes an ion beam directing unit **120** including a first deflection unit **121** for deflecting the ion beam **101** along a first lateral direction (x-axis) and a second deflection unit **122** for deflecting the ion beam **101** along a second lateral direction (y-axis) which may be orthogonal to the first lateral direction. Each of the deflection units **121**, **122** may deflect the ion beam symmetrically with respect to a center position of the ion beam **101**.

A substrate support **190** fixes a substrate **200** such that a center point **105** of the substrate **200** is arranged in the center position of the ion beam **101**.

The substrate **200** may be a circular substrate, for example a standard semiconductor wafer with any diameter, e.g. at least 25.4 mm. The semiconductor wafer may be a silicon wafer, an SOI (silicon-on-insulator) wafer, e.g., an SOG (silicon-on-glass) wafer, or a substrate of another single-crystalline semiconductor material such as silicon carbide SiC, gallium arsenide GaAs, gallium nitride GaN, any other $A_{III}B_V$ semiconductor, germanium Ge or a silicon-germanium crystal SiGe, by way of example. According to another embodiment, the substrate **200** may be a disc-shaped substrate cut out from a semiconductor wafer, e.g. by a laser beam

The substrate support **190** may align the substrate **200** such that an exposed process surface **201** of the substrate **200** is perpendicular to the ion beam **101** in its center position. According to other embodiments, the substrate **200** is tilted to the ion beam in its center position by at most 10 degree, for example by about 7 degrees.

A controller **150** is coupled to the ion beam directing unit **120** and controls the deflection of the ion beam **101** to effect a relative movement between the ion beam **101**, which passes the ion beam directing unit **120**, and the substrate support **190** such that a beam track **109** of the ion beam **101** on the process surface **201** is a spiral or includes circles. For example, the controller **150** may be electrically connected or coupled to the first deflection unit **121** and to the second deflection unit **122** and effects a modulation of a deflection voltage applied to the first and second deflection units **121**, **122** in an appropriate way.

As illustrated in FIGS. **1**B and **1**C each of the deflection units **121**, **122** may include two deflection plates **121***a*, **121***b*, **122***a*, **122***b* on opposing sides of the ion beam **101**, respectively. The control unit **150** may apply a first deflection signal s**1**(t) to the first deflection unit **121** and a second deflection signal s**2**(t) to the second deflection unit **122**. According to the illustrated embodiment the first deflection signal s**1**(t) is applied to a first deflection plate **121***a* of the first deflection unit **121** and the second deflection signal s**2**(t) is applied to the first deflection plate **122***a* of the second deflection unit **122**, whereby the second deflection plates **121***b*, **122***b* are grounded. According to other embodiments the controller unit **150** may apply differential deflection signals to both deflection plates of each deflection unit **121**, **122**.

The amplitudes of the two deflection signals s**1**(t), s**2**(t) may fluctuate around mean values defining a center position of the ion beam **101**. The two deflection signals s**1**(t), s**2**(t) may be sinusoidal signals, which may have the same frequency and which may be phase-shifted to each other by Π/2 such that the ion beam follows the surface of a cone and for each complete oscillation the ion beam **101** surrounds the center point **105** once between the center point **105** and a lateral area **203** tilted to the process surface **201**. The amplitudes of the two deflection signals s**1**(t), s**2**(t) determine the distance of the circulation to the center point **105**.

According to an embodiment with the process surface **201** perpendicular to the ion beam **101** in its center position the amplitudes of the two deflection signals s**1**(t), s**2**(t) may be equal such that for each complete oscillation the beam track **109** on the process surface **201** is a circle. According to embodiments with the process surface **201** tilted to the ion beam **101** in its center position the amplitude ratio of the two deflection signals s**1**(t), s**2**(t) may be adjusted in a way such that the beam track **109** includes circles around the center point **105**.

For achieving a homogeneous implant dose across the process surface **201** the amplitudes of the deflection signals s**1**(t), s**2**(t) may be varied proportional to 1/r at a fixed amplitude ratio, with r indicating the distance of the ion beam **101** to the center point **105** on the process surface **201**. Starting from deflection signals for homogeneous implant doses rotational-symmetric, e.g., circular implantation profiles may be obtained by modifying, at the same implant current, the frequency of the first and second deflection signals s**1**(t), s**2**(t) resulting in a modification of the implant dose along the beam track **109**, or by modifying, at the same amplitude ratio, the amplitude gradient of the deflection signals s**1**(t), s**2**(t) resulting in a radial modification of the density of circulations of the beam track **109**, by way of example.

According to the embodiment of FIG. **1**B the amplitudes of the deflection signals s**1**(t), s**2**(t) are constant during one or more complete circulations and are simultaneously changed, at the same amplitude ratio, after the beam track **109** has completed one or more complete circulations. The beam track **109** includes circles of different diameters and the impurity distribution is circular. According to another embodiment the frequency of both deflection signals s**1**(t), s**2**(t) may vary for only a portion of a circle such that the implant dose varies along the beam track **109**.

According to the embodiment of FIG. **1**C the controller **150** of FIG. **1**A steadily increases the amplitudes of both deflection signals s**1**(t), s**2**(t) such that the beam track **109** of the ion beam **101** on the process surface **201** is a spiral. The controller **150** may control the deflection units **121**, **122** such that the beam track **109** winds inwardly or outwardly. The beam track **109** may cross the whole substrate **200** between the center point **105** and a lateral area **203** or a portion thereof. The frequency of both deflection signals s**1**(t), s**2**(t) may vary for only a portion of a circulation such that the implant dose varies along the beam track **109**.

FIG. **1**D shows impurity concentration profiles in the semiconductor substrate **200** which can be obtained by using the ion implantation apparatus **100** of FIG. **1**A. For profile **302**, the beam track **109** crosses only an inner portion including the center point **105**, for profile **304** the beam track **109** crosses an outer portion along the lateral area **203** and for profile **306** a ring portion distant to both the center point **105** and the lateral area **203**. The ion implantation apparatus **100** is adapted to form rotational-symmetric, e.g., circular impurity regions and a variation of doping along circles or a spiral.

Where for circular impurity profiles conventional ion implanters performing linear line-by-line scanning along the x-axis or along zig-zag paths require rather complex and time-consuming programming steps for locally varying the implant dose by modifying the scans, the ion implantation apparatus **100** achieves a similar effect at less effort and with better local resolution.

The ion implantation apparatus **100** of FIG. **2**A includes an ion beam source **110** emitting an ion beam **101** and an ion beam directing unit **120** that deflects the emitted ion beam **101** along a linear direction, e.g., along the x-axis. The ion beam directing unit **120** may include a deflection unit with two deflection plates **120***a*, **120***b*. In addition, a motor drive unit **180** rotates the substrate support **190** around a center point **105** of a substrate **200** fixed on the substrate support **190** in a plane that is perpendicular to the ion beam **101** in its central position or slanted by at most 10 degree, for example by about 7 degree with respect to the plane perpendicular to the ion beam **101** in its center position.

The controller unit **150** may control the ion beam direction unit **120** such that the ion beam **101** moves in a plane spanned by a normal to the process surface **201** or tilted to the normal by a tilt angle of at most 10 degree, for example about 7 degree. In addition, the controller **150** may detect and/or control the rotational speed of the substrate support **190** by monitoring or controlling the motor drive unit **180** whose shaft is coupled to the substrate support **190**. Section line **108** indicates the cross-sectional line between the plane in which the ion beam **101** moves and the process surface **201** of the substrate **200**. The section line **108** includes the center point **105**.

The deflection signal s**3**(t) may be a linearly decreasing or increasing signal **201**. For a constant rotational speed of the substrate support **190** the deflection signal s**3**(t) may change only slowly close to the lateral area **203** and faster with decreasing distance to the center point **105** as shown in FIG. **2**B. For example, with r indicating the distance to the center point **105** the deflection signal s**3**(t) may change at a rate 1/r as indicated by signal **202** for achieving a homogeneous impurity distribution.

According to other embodiments the deflection signal s**3**(t) may be an amplitude modulated periodic signal **203**, wherein the frequency of the periodic signal **203** may be lower than the rotational rate of the substrate support **190** also as shown in FIG. **2**B. According to an embodiment the rotational rate is at least ten times as high as the linear scan rate of the deflection signal s**3**(t). During each complete linear scan the ion beam **101** may circulate at least ten times around the center point **105** for achieving a sufficient homogeneous impurity profile.

FIGS. **3**A to **3**C refer to wafer-scale semiconductor devices **200***x* obtained by using the ion implantation apparatuses **100** of FIGS. **1**A and **2**A on circular semiconductor substrates. The wafer-scale semiconductor devices **200***x* are based on cylindrical semiconductor bodies **205** whose diameter may correspond to a standard wafer diameter, e.g., 25.4 mm, 50.8 mm, 76.2 mm, 100 mm, 125 mm, 150 mm, 200 mm, or 300 mm or any other value greater than 10 mm. A wafer-scale semiconductor device **200***x* is a single semiconductor die and not integrated in a wafer composite that includes a plurality of identical semiconductor dies.

The semiconductor device **200***x* of FIG. **3**A may be a disc-shaped thyristor or a disc-shaped semiconductor diode with approximately circular lateral base areas **201**, **202**. In a thyristor on-state or in the forward mode of a semiconductor diode mobile charge carriers flood a drift zone of the semiconductor body between the two opposing base areas **201**, **202**. When the thyristor changes to an off-state or blocking state or when the semiconductor diode changes to a blocking mode, the respective semiconductor device **200***x* commutates wherein the mobile charge carriers are removed from the drift zone. Typically an edge area **290** directly adjoining a lateral area **203** connecting the base areas **201**, **202** is less effective in removing the mobile charge carriers from the drift zone, because, for example, electrode structures do not reach the lateral area **203**.

In the semiconductor device **200***x* a circular implant of impurities with a radial concentration variation may result in a ring-shaped circular implant zone **295** in the edge area **290** around a center point **105**, wherein the circular implant zone **295** may be spaced from the lateral surface **203** or may directly adjoin the lateral surface **203**. In the circular implant zone **295** implanted ions such as protons or helium (He) ions may generate particle-induced crystal defects in the silicon crystal lattice. The crystal defects significantly reduce the charge carrier life time in the circular implant zone **295** such that less charge carriers have to be removed from the edge area **290** when the semiconductor device **200***x* commutates. As a result the dynamic losses in the semiconductor device **200***x* are lower than without the circular implant zone **295**.

The implantation-induced defect concentration in the circular implant zone **295** may continuously or in steps increase in radial direction with increasing distance to the center point **105**. Forming the circular implant zone **295** by the circular implantation method described above may save a graded implant mask and may achieve better circular uniformity than unmasked implants based on linear scans.

The semiconductor device **200***x* of FIG. **3**B may be a semiconductor diode or a thyristor including a heavily doped pedestal layer **252** forming an ohmic contact with a metal-containing rear side electrode **251**, a low doped drift zone **255** as well as a field stop layer **253** between the low doped drift zone **255** and the pedestal layer **252**.

The pedestal layer **252** may have a central portion **252***a* having a high partial transistor gain around the center axis **207** and a circular outer portion **252***b* with low partial transistor gain along the lateral area **203**. At lower partial transistor gain less charge carriers are injected into the edge area **290** such that less charge carriers have to be removed from the edge area **290** during commutation. Reducing the number of charge carriers during commutation in the edge area **290** also increases the dynamic dielectric strength of the edge area **290** and avalanche breakdown mainly occurs between the edge area **290** and the center axis **207**.

The field stop layer **253** may be a circular implant zone with a circular impurity profile including a circular first portion **253***a* around the center point **105**, a circular second portion **253***b* enclosing and surrounding the first portion **253***a* and a circular third portion **253***c* between the second portion **253***b* and the lateral area **203**.

The field stop layer **253** may be formed by circular implantation of ions such as protons that generate circularly-distributed radiation-induced crystal defects. During an anneal at temperatures between 270° C. and 500° C. particle-related donors such as hydrogen-related donors may form at the radiation-induced crystal defects, wherein the hydrogen-related donors may be hydrogen-decorated intrinsic point defect complexes.

In case the semiconductor device **200**x is a thyristor, the pedestal and field stop layers **252**, **253** form a pn-junction. The impurity concentration in the third portion **253**c of the field stop layer **253** is higher than the impurity concentration in the second portion **253**b. The impurity concentration in the second portion **253**b is higher than the impurity concentration in the first portion **253**a. The higher doped portion **253**c prevents a depletion zone associated with an avalanche current from a critical punch through to the rear side electrode **251** in the edge area **290**.

The circular patterns of the pedestal layer **252** and the field stop layer **253** result in high dynamic robustness and high avalanche current strength.

In case the semiconductor device **200**x is a semiconductor diode the pedestal and field stop layers **252**, **253** form a unipolar homojunction, e.g. an nn^+ or pp^+ junction. The impurity concentration in the third portion **253**c of the field stop layer **253** is lower than the impurity concentration in the second portion **253**b. The impurity concentration in the second portion **253**b is lower than the impurity concentration in the first portion **253**a. In addition to the impurity concentration, the vertical extensions of the first, second, and third portions **253**a, **253**b, **253**c may be varied.

The circular pattern of the field stop layer **253** may be adjusted to increase the blocking capability in the edge area **290**.

In FIG. **3**C the semiconductor device **200**x is a GTO (gate turn-off) thyristor with a semiconductor body **205** including a p-type pedestal layer **253** effective as anode layer and forming an ohmic contact with a rear side electrode **251** effective as anode electrode, an n-type base layer **255** forming a pn junction with the pedestal layer **253**, a p-type base layer **257** forming a pn junction with the n-type base layer **255**, and heavily n-type cathode zones **259** forming pn junctions with the p-type base layer **257**. On a first base area **201** portions of a cathode electrode **258** form ohmic contacts with the cathode zones **259** and portions of a gate electrode **256** form ohmic contacts with the p-type base layer **257**.

When a current supplied through the gate electrode portions **256** exceeds a threshold value, ignition starts close to the respective gate electrode portion **256** and propagates to the center of the cathode zones **259**. For turning the GTO off, a negative gate current is supplied through the gate electrode portions **256** and within the p-type base layer **257** holes flow in radial direction to the gate electrode portions **256**. The time for switching off a cathode zone **259** depends on the impurity concentration in the p-type base layer **257** and the timing of the gate signal at the gate electrode portions **256**. Due to the radial variation of the ohmic line resistance, the gate signal may be delayed between gate electrode portions **256** closer to a supply point of the gate signal and gate electrode portions **256** more distant to the supply point.

A suitable radial variation of a defect concentration with a defect density increasing in radial direction and hence a radial decrease of the charge carrier life time in the n-type base zone **257** may compensate for the radial variation of the effective resistance of the gate metallization and the gate signal propagation delay between ring-shaped gate electrode portions **256**. With a defect density increasing in radial direction the cathode zones **259** are switched off within a narrower time span and a maximum current which the thyristor can switch off may be significantly increased.

Generally, a radial variation of defect and/or dopant concentration profiles may be used for a better tradeoff between the static blocking capability of semiconductor devices and the softness of a current gradient during switching off.

FIGS. **4**A to **4**D refer to embodiments applying a circular ion implantation to semiconductor substrates such as semiconductor wafers.

Silicon semiconductor wafers, e.g., wafers with a diameter of 300 mm, may be obtained from molten silicon using a Czochralski process. A rod with a seed crystal dips into the molten silicon. Single-crystalline silicon crystallizes at the seed crystal and when the rod is slowly pulled out of the melt, the silicon crystal forms a cylindrical ingot which follows the rod. The rod may be rotated during the crystal growth process. M:Cz silicon wafers are obtained from a magnetic Czochralski process using an external magnetic field that suppresses or controls a melt flow in the molten silicon.

Cz and m:Cz wafers may contain interstitial oxygen atoms which in combination with crystal defects may be effective as donors. Typically, a high energetic proton implant is used to generate a homogeneous background donor concentration in at least a partial layer of the semiconductor wafer, e.g. in a layer that corresponds to a lightly doped drift zone of the finalized devices. The implanted protons may interact with the intrinsic oxygen and with crystal defects generated by the implant to generate a doping effective as donors. The intrinsic oxygen distribution in a virgin m:Cz wafer significantly affects the local efficiency of the proton implant as well as the specific ohmic resistance distribution.

It could be demonstrated by the inventors that the Czochralski m:Cz processes result in approximately circular inhomogeneities of the oxygen distribution in the silicon ingot and the semiconductor wafers obtained from the silicon ingot.

FIG. **4**A shows the specific ohmic resistance distribution in an m:Cz silicon wafer with a radius R. The specific resistance includes maxima and minima in an approximately circular pattern with respect to a center point at r=0. The variation of the specific resistance is about 15% of a mean value in a central region around the center point.

FIG. **4**B schematically shows the intrinsic oxygen density distribution in an m:Cz silicon wafer obtained from an ingot manufactured in a magnetic Czochralski process. The oxygen concentration in a center portion is about 11% higher than along the lateral area of the semiconductor wafer.

FIG. **4**C illustrates rectangles assigned to semiconductor dies obtained from a single m:Cz silicon wafer, wherein dark rectangles indicate high charge carrier concentrations and light rectangles indicate low charge carrier concentrations. Yet at the very beginning of manufacturing, semiconductor dies assigned to different wafer areas differ significantly with respect to the background charge carrier concentration. Though obtained from the same m:Cz silicon wafer, such semiconductor devices obtained from an edge region of the m:Cz silicon wafer may have charge carrier concentrations in low-doped regions, e.g. drift zones, which significantly deviate from the charge carrier concentrations in semiconductor devices obtained from a central region of the same m:Cz silicon wafer. The differences add to the fluctuations in further processes.

Implantation of ions such as protons using a circular regime may compensate for circular distributions of the oxygen distribution. For example, when the semiconductor wafer receives a background impurity concentration, a suitable implant of protons may compensate for the differences in the background concentration.

For conventional ion implanters which typically modify a local impurity profile in an x-y grid a laborious and complex programming compensates for the inherent impurity concentration in the virgin Czochralski wafer. On the other hand, the circular implantation scheme as described above provides a simple and cost-effective method for compensating circular process inhomogeneities introduced, e.g., by the Czochralski process, e.g. in wafers having a diameter of 300 mm and more.

Accordingly, a method of manufacturing semiconductor devices may include pulling a single crystalline silicon ingot from fluidified silicon in a Czochralski process and obtaining, for example by cutting or sawing, semiconductor wafers from the silicon ingot.

The distribution of the resulting effective charge carrier concentration in the semiconductor wafer is determined, for example by measurement, and may be approximated by a circular approximation. Then a compensation profile for compensating the approximated circular impurity distribution may be determined and transferred to the controller unit **150** of the ion implantation apparatus **100** of FIG. **1**A or **2**A. The background implant is performed, wherein uniformity of the resulting impurity concentration profile of the Czochralski wafer is improved.

FIG. **4**D schematically shows the radial oxygen distribution **312** in a virgin Czochralski m:Cz silicon wafer, the circular approximation **314**, the profile of the compensation implant **316** using protons and the resulting effective donor profile **318**. Where the initial oxygen concentration and the concentration of oxygen-induced thermal donors are low, more protons are implanted than where the initial oxygen concentration and the concentration of oxygen-induced thermal donors are high.

The compensation implant **316** forms a circular implant zone containing hydrogen-related donors. A radial concentration variation of the compensation implant **316** around the center point of the semiconductor wafer may compensate to some degree a radial variation of the concentration of the oxygen-induced donors. The resulting effective donor profile **318**, which is the sum of the concentrations of the hydrogen-related donors and the oxygen-induced thermal donors, can be tailored such that a variation of the sum of the concentrations is at most 25%, e.g. at most 15% or even below 10%.

The circular implant compensates for effects caused by the oxygen distribution.

FIG. **5** refers to an ion implantation method as well as to a method of manufacturing a semiconductor device. An ion beam is directed on a substrate (**502**). A relative movement between the ion beam and the substrate is controlled such that a beam track of the ion beam on a surface of the substrate is a spiral or includes a circle around the center point of the substrate (**504**).

A method of manufacturing a semiconductor device includes directing an ion beam onto a substrate and controlling a relative movement between the ion beam and the substrate such that a beam track of the ion beam is a spiral or includes circles. A single-crystalline silicon ingot may be pulled out from fluidified silicon and the substrate may be obtained by sawing the silicon ingot orthogonal to its longitudinal axis.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a variety of alternate and/or equivalent implementations may be substituted for the specific embodiments shown and described without departing from the scope of the present invention. This application is intended to cover any adaptations or variations of the specific embodiments discussed herein. Therefore, it is intended that this invention be limited only by the claims and the equivalents thereof.

What is claimed is:

1. A semiconductor substrate, comprising:

a circular wafer-scale semiconductor body; and

a circular implant zone with a radial variation of doping around a center point in the semiconductor body, wherein

the circular implant zone is a circular defect zone including hydrogen-related donors with a radial concentration variation around the center point of the semiconductor substrate, and

a variation of a sum of the concentrations of the hydrogen-related donors and oxygen-induced thermal donors is at most 25%.

2. A semiconductor device comprising a semiconductor substrate, the semiconductor substrate comprising:

a circular wafer-scale semiconductor body; and

a circular implant zone with a radial variation of doping around a center point in the semiconductor body, and wherein

the circular implant zone directly adjoins a pedestal layer directly adjoining a base area of the semiconductor body, and

an impurity concentration in the pedestal layer is equal to or greater than a minimum impurity concentration for an ohmic contact between the pedestal layer and a metal-containing electrode directly adjoining the base area.

3. The semiconductor device of claim **2**, wherein

the circular implant zone contains radiation-induced dopants.

4. The semiconductor device of claim **2**, wherein

the circular implant zone contains doping atoms.

5. The semiconductor device of claim **2**, wherein

the circular implant zone directly adjoins a lateral area of the circular semiconductor body.

6. The semiconductor device of claim **2**, wherein

the semiconductor device is a gate turn-off thyristor and the circular implant zone is a p-type or n-type base layer.

7. The semiconductor device of claim **2**, wherein

a width of the circular implant zone is smaller than a radius of the circular semiconductor body.

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